

# Sustainable Software Ecosystems: Software Engineers, Domain Scientists, and Engineers Collaborating for Science

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## Abstract

The development of scientific software is often a partnership between domain scientists and scientific software engineers. It is especially important to embrace these collaborations when developing advanced scientific software, where sustainability, reproducibility, and extensibility are important. In the ideal case, as discussed in this manuscript, this brings together teams composed of the world’s foremost scientific experts in a given field with seasoned software developers experienced in forming highly collaborative teams working on software to further scientific research [1].

In addition to enabling scientists to perform research more effectively, enriching the field by offering well-engineered software, sustainable software frees researchers from performing tasks that do not offer the rewards that their institution values. When these software platforms are developed as collaborative R&D platforms, it also empowers both the team developing the software and the wider community. We will present case studies of two DOE sponsored SBIR projects—one in nuclear engineering that began in 2013, and another in scanning transmission electron microscopy tomography (S/TEM) for materials. These projects build upon the Visualization Toolkit (VTK), and ParaView, each of which has over a decade of development history funded by multiple agencies in collaboration with many institutions [2].

It is clear that there are examples where heroic efforts created sustainable software, but this is clearly the exception—not the rule. Many of these projects required significant sacrifice, and some risky bets outside of established career paths. Their efforts should be applauded, but we must as a community develop the necessary governance, policy, and credit mechanisms to make sustainable, reproducible scientific software a reality. Its importance in the sphere of scientific investigation is getting increasingly important. Many of these points were touched upon in the the first Workshop on Sustainable Software Ecosystems for Open Science [3].

## Governance

One of the critical challenges faced when starting a new project is that of forming the right project governance. Most projects are developed by small teams, but if the right pieces are put in place a project can grow from humble beginnings to effectively change the way research is done in a field. There are many factors that contribute to forming a vibrant and sustainable community. These include the software licenses applied, version control, mailing lists, bug trackers, testing framework, language(s) used for development, as well as higher level policies such as the contribution model used, empowering long term evangelists to move the project between funding sources, and finding advocates to help promote the project.

Kitware, Inc. has operated as a for-profit company providing software services and managing large software projects partnering with hundreds of institutions for over 16 years. Over this time it has experimented with several approaches, settling on one common approach that has worked well for several major projects, such as VTK and ParaView [2]. This approach involves partnering with national laboratories, universities and/or other organizations from industry where appropriate to form teams dedicated to engineering cross-platform, open source collaborative R&D platforms. Kitware has traditionally focused on solutions written in C++, wrapped in Python (and possibly other languages), although more recently this has extended to developing more software directly in Python, and web components in HTML5, JavaScript and WebGL.

These platforms are developed openly, with the version control, software quality dashboards, mailing lists, and other resources all publicly hosted. Permissive open source licenses are used, such as the 3-clause BSD license, and the Apache 2.0 license for software, and Creative Commons licenses for data. Software experts work hand-in-hand with partners on focused applications, extending the underlying libraries where necessary and/or

desirable. The focused applications benefit from the significant infrastructure developed in the software frameworks, and the frameworks benefit from additional features, bug fixes, and enhancements added as part of the project. Kitware experts usually work across more than one project, and will usually develop skills over several application domains. This model has been used to develop a large number of projects, including a new build system (CMake) that is now one of the most widely used C/C++ build systems.

This model has been instrumental in securing funding from a large number of funding agencies using multiple funding vehicles, along with the development of bespoke commercial applications building upon the same frameworks.

## Policies

In order for sustainable software to become a priority the funding agencies, universities, national labs and other institutions must adjust their policies to reward those who develop and sustain software. The development of software is a time consuming process, and is often not viewed in the same high regard as publishing original research, despite the fact that it can have much wider impacts. As the volume of data increases, and original research depends more critically upon the data collection, analysis, and visualization of its outputs using increasingly sophisticated software sustainable models for development of such software becomes critical [3].

Software developed in a sustainable way, across multiple institutions not only reduces waste (through the unnecessary reinvention of the wheel), it can lead to new research that would not otherwise have been possible—“standing on the shoulders of software giants”. If open, permissive licenses are used we do not unfairly restrict the application areas, and if the throw-away software developed as part of other research projects is published under open licenses that can be integrated into larger frameworks. If papers are able to describe new additions to a tested software framework they can go beyond the error prone description of algorithms using pseudocode to concrete implementations with tests that can be verified independently.

## Credit

One of the most important aspects of sustainable software for science is that of credit—cultivating sustainability requires an environment where credit and incentives are in place to foster career paths and growth of long-term projects [1, 2, 3]. The software development landscape is moving in the right direction—where DOIs can be generated for software versions in Git repositories on GitHub, data on Figshare, and other repositories. Metadata markup is being developed to more efficiently point out who authored software, and how it should be cited. Peer-reviewed papers addressing the development

of software, and issues around software are becoming more common.

Download statistics, service accesses, and metrics based around blogging and social media can be used, in approaches such as altmetrics, to form a basis for awarding credit for work, measuring wider impact, and building up a scientific software developers portfolio. We must consider whether this is enough, and whether funding agencies should more strongly mandate for the development of sustainable software in science to avoid the waste in much the same way as was done for data. Software sustainability is more complex, but also more important as research is more computationally intensive than ever before. Reproducibility is critical if we realistically expect to be able to build upon the work that came before.

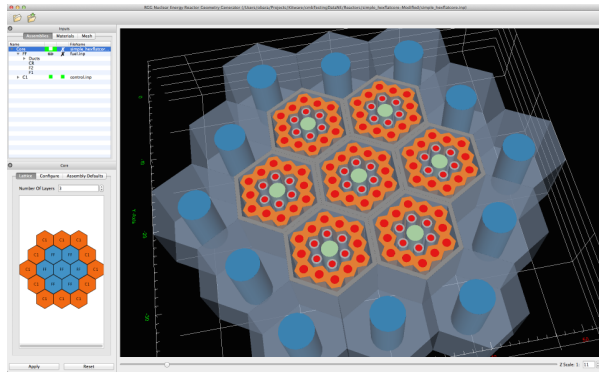
## Case Studies

In addition to mature, and proven projects, Kitware is at various stages of developing new projects across a number of application domains. Here we present two such examples that are funded by the Department of Energy (DOE) SBIR program, the nuclear energy systems modeling is currently in Phase II, and S/TEM materials tomography project is just a few months into Phase I of the program.

### Computational Analysis of Nuclear Energy Systems

Computational analysis of nuclear energy systems is a complex multi-physics problem. Fundamental to the solution of these problems is an appropriate computational discrete mesh of the geometric domain of interest. A nuclear reactor core will involve a large number of components (e.g fuel and control rod, assemblies and instrumentation packages) and the simulation involves several physical phenomena such as neutron transport, heat transfer, fluid flow, and thermal expansion. The reactor cores are typically arranged in either a rectangular lattice for water-cooled reactors, or a hexagonal lattice for sodium and gas-cooled reactors. Mesh generation for these complex geometries typically require the coupling of various toolkits such as Meshkit from Argonne National Laboratory [4], Cubit from Sandia National Laboratory, and OpenCascade from OpenCascade SAS.

While generation of geometry and mesh models for reactor cores can be a difficult process, MeshKit, developed by our partners Dr. Rajeev Jain of Argonne National Laboratory and Dr. Timothy Tautges of the University of Wisconsin Madison, takes advantage of the various lattice structures that exist within the core in order to reduce the complexity of model and mesh construction. Based on a small set of parameters, geometry and mesh are constructed for a variety of reactor core types arranged as both rectangular and hexagonal lattices. While Meshkit is a powerful suite of tool, its target end-users are currently the developers themselves,



**Figure 1:** A screenshot of the RGG application modeling a hexagonal-based reactor core.

and not the nuclear engineers with simulation problems.

To address this problem, an open source GUI tool called the Reactor Geometry (and mesh) Generator (RGG) is being developed as part of a DOE Nuclear Energy Fast Track SBIR. RGG is a cross-platform solution based upon the VTK/ParaView and Meshkit frameworks. The first generation of the tool was developed during the project's Phase I effort and is freely available. This version runs on Macs, Windows, and Linux platforms. The current underlying MeshKit workflows does require Cubit to generate the required meshes, but will be extended with open source mesh generators early in Phase II.

During the past year, the RGG application has been presented at workshops hosted by the DOE Nuclear Energy Advanced Modeling and Simulation (NEAMS) Program and the Consortium for Advanced Simulation of Light Water Reactors (CASL). The feedback provided by the attending scientists and engineers was invaluable and led to enhancements realized in RGG version 1.0.

In addition to contributing to the nuclear energy community, the RGG effort has also contributed back to various open source activities. This included identifying and correcting various deficiencies within VTK and MeshKit as well as adding several enhancements. In particular to MeshKit, RGG has simplified its building process and made it possible to deploy some of MeshKit's components to the Windows platform. RGG has directly influenced MeshKit's reactor modeling workflow to include the ability to share essential parametric information between assemblies in order to generate valid meshes; resulting in a reduction of potential end-user error. These contributions are essential to the sustainability of the Meshkit software.

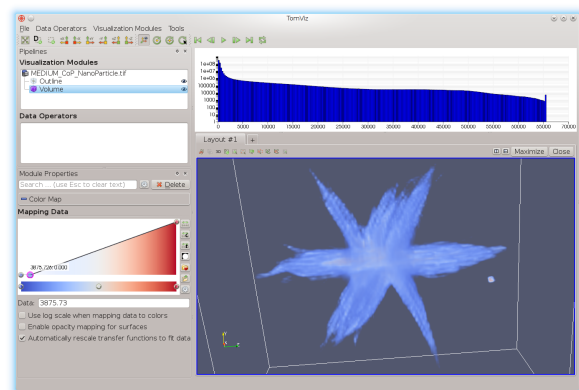
## Atomic Resolution Materials Tomography

Atomic resolution S/TEM tomography for materials science is a challenging area of materials characterization with great potential. Dr. Hanwell is the principal investigator for this project, with some background in

similar techniques, partnering with Prof. Muller and Dr. Hovden at Cornell University. The technique has seen a number of major advances in recent years, resulting in astounding three-dimensional images of nanosystems with atomic resolution attainable under the right conditions. As with a number of experimental techniques the acquisition and analysis software has not necessarily kept pace with the hardware.

Researchers are routinely recording data at  $1024 \times 1024 \times 1024$ , and sometimes even higher resolutions. The data treatment for S/TEM tomography data can be quite complex, with the current state-of-the-art often involving manual alignment of the individual tilts, custom MATLAB code to perform the reconstructions, and once the reconstructed data is ready the data size can lead to problems when visualizing and analyzing the data. The software currently available often lacks necessary features, and is not capable of effectively handling data of this size. Due to the complex nature of data collection, alignment, reconstruction and analysis it is also impossible to save the steps taken from raw data to final reconstructed image.

A collaborative SBIR proposal was submitted recommending an open source, cross-platform solution based on the VTK and ParaView frameworks, extending them and creating a focused S/TEM tomography application, named TomViz, to address these deficiencies and offer an integrated application. The Phase I project focuses on demonstrating viability, and developing an application that can align image slices, perform reconstruction in an extensible Python environment built into the application, and save the complete state of analysis using state files that can be shared, and even offered as supporting data in publications [5].



**Figure 2:** The tomviz application showing a tomographic reconstruction of a nanoparticle (volume rendering), with interactive histogram, and transfer function editor.

Many of the extensions have been contributed to the VTK and ParaView projects, making them available to

the wider community. The TomViz application is available as a binary installer for Windows, and Mac, with full source available for other platforms. The Kitware and Cornell team will attend the Microscopy and Microanalysis conference in August to present the first release of the software, and has already visited Cornell to gather feedback from a number of TEM microscopists interested in using the software in their research. Significant advances have already been demonstrated in the analysis of reconstructed volumes, with work on alignment and reconstruction currently under active development in partnership with our university partners in preparation for the scientific meeting in August. The application is shown in Figure 2, where a tomographic reconstruction of a nanoparticle is shown.

## Conclusions

Software development is often seen as an afterthought when purchasing new equipment, or an incidental output of research. We have presented some brief case studies of early-stage projects being developed by software engineering experts in partnership with national laboratories and universities. Without the partnerships with software specialists researchers in these areas would not have been able to develop software capable of tackling their research problems so effectively, nor would they have been motivated due to current reward mechanisms. In addition to the immediate benefits described, Kitware, as a for-profit company, offers support services for the software, along with consultancy services to provide new features not developed as part of the initial project that may receive little or no interest from the research community.

Software development is inherently a service-based industry, with the majority of global software development being performed as a service. As a result of abandoning the traditional license-based model Kitware has become an engine of change, enabling the next generation of researchers to tackle some of the most computationally challenging problems through the use of open, verified software with a process backed by professional software developers. All source code is available, and every step of the visualization and analysis process can be verified, with any bugs rapidly corrected by using an established contribution model to ensure the maximum number of people benefit. The company has a demonstrated ability to deliver quality software, enabling open, reproducible research that is both sustainable and through the use of permissive open source licenses promotes shared ownership of frameworks by the wider scientific community.

As the scientific community embraces open, reproducible scientific research paradigms it is critical that the software infrastructure and applications keep pace. It is not enough to simply treat software as a black-box, and expect it to be developed because it is needed. We need to change the research landscape to encourage

teaming, take projects beyond single-person, or even single group projects. Instead of rewarding only papers and citations we must embrace and encourage low-friction collaboration, rewarding contributions to larger, more established projects to avoid unnecessary reinvention of the wheel. We must also fund and reward projects placing an emphasis on software engineering principles, automated testing, code review, and community engagement using software processes that support collaboration.

The computational power, and volumes of data available in all fields of research are increasing. It is critical that we as a community embrace open, and reproducible science, along with the role that software plays in this ecosystem. Funding must be made available not only for novel research, but for essential maintenance and improvement of established projects in much the same way as central user facilities are maintained. Finally, sustainable software must fill an important need, and be architected well enough so that it can be used in flexible and evolving ways.

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